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UTILITY APPLICATION AND APPLICATION FEE TRANSMITTAL (1.53(b))

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Sir:

Transmitted herewith for filing is the patent application of

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For: AN IMPROVED IN-BAND-ON-CHANNEL (IBOC) SYSTEM AND METHODS OF
OPERATION USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING
(OFDM) WITH TIMING AND FREQUENCY OFFSET CORRECTION

Enclosed are:

[X]   __10__ page(s) of specification, __1__ page(s) of Abstract, __6__ page(s) of claims

[X]   __4__ sheets of drawing   [x]   formal   [ ]   informal

[X]   __4__ page(s) of Declaration and Power of Attorney

      [ ]   Unsigned
      [x]   Newly Executed
      [ ]   Copy from prior application

          [ ]   Deletion of inventors including Signed Statement under 37 C.F.R. § 1.63(d)(2)

[ ]   Incorporation by Reference: The entire disclosure of the prior application, from which a copy of the
combined declaration and power of attorney is supplied herein, is considered as being part of the disclosure
of the accompanying application and is incorporated herein by reference.

[ ]   Microfiche Computer Program (Appendix)

[ ]   ____ page(s) of Sequence Listing

      [ ]   computer readable disk containing Sequence Listing

      [ ]   Statement under 37 C.F.R. § 1.821(f) that computer and paper copies of the Sequence Listing are
the same

6630_1

[X]   Assignment Papers (assignment cover sheet and assignment documents)

      [x]   Charge Fee(s) $40.00 for recording the Assignment to Deposit Account No. 12-2325 Order No. CUPO 20-2. A DUPLICATE COPY OF THIS SHEET IS ATTACHED

      [ ]   Assignment papers filed in parent application Serial No. _____.

      [ ]   Certification of chain of title pursuant to 37 C.F.R. § 3.73(b).

[ ]   Foreign priority is claimed under 35 U.S.C. § 119 from _____ Patent Application(s) No. _____ dated _____ .

      [ ]   Priority document(s) will be submitted at a later date.

      [ ]   Priority document(s) is/are submitted herewith.

[ ]   Information Disclosure Statement

      [ ]   Copy of ____ cited references

[ ]   Preliminary Amendment

[X]   Return receipt postcard (MPEP 503)

[ ]   This is a [ ] continuation [ ] divisional [ ] continuation-in-part (C-I-P) of prior application serial no. _____.

      [ ]   Cancel in this application original claims _____ of the parent application before calculating the filing fee. (At least one original independent claim must be retained for filing purposes.)

      [ ]   A preliminary Amendment is enclosed. (Claims added by this Amendment have been properly numbered consecutively beginning with the number following the highest numbered original claim in the prior application.

[ ]   The status of the parent application is as follows:

      [ ]   A Petition For Extension of Time and a Fee therefor has been or is being filed in the parent application to extend the term for action in the parent application until _____.

      [ ]   A copy of the Petition for Extension of Time in the co-pending parent application is attached.

      [ ]   No Petition For Extension of Time and Fee therefor are necessary in the co-pending parent application.

[ ]   Please abandon the parent application at a time while the parent application is pending or at a time when the petition for extension of time in that application is granted and while this application is pending has been granted a filing date, so as to make this application co-pending.

      [ ]   Transfer the drawing(s) from the patent application to this application.

[ ]   Amend the specification by inserting before the first line the sentence:
This is a [ ] continuation [ ] divisional [ ] continuation-in-part of co-pending application Serial No._____   filed _____ .

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I.   CALCULATION OF APPLICATION FEE

	Number Filed		Number Extra		Rate	Basic Fee $760.00
Total Claims	21	-20=	1	x	$18.00	$18.00
Independent Claims	3	- 3=	0	x	$78.00	$0.00

Multiple Dependent Claims

[ ]	yes	Additional Fee	=	$260.00	$0.00
[x]	no	Additional Fee	=	NONE	

TOTAL $778.00

[ ]   A statement claiming small entity status is attached or has been filed in the above-identified parent application and its benefit under 37 C.F.R. § 1.28(a) is hereby claimed. Reduced fees under 37 C.F.R. § 1.9(F) (50% of total) paid herewith $ _____.

[ ]   A check in the amount of $ _____ in payment of the application filing fees is attached.

[X]   Charge Fee(s) to Deposit Account No. 12-2325 Order No. CUPO 20-2. A DUPLICATE COPY OF THIS SHEET IS ATTACHED.

[X]   The Assistant Commissioner is hereby authorized to charge any additional fees which may be required for filing this application, or credit any overpayment to Deposit Account No. 12-2325. A DUPLICATE COPY OF THIS SHEET IS ATTACHED.
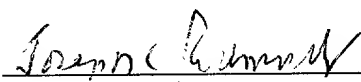
Respectfully submitted,

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AN IMPROVED IN-BAND-ON-CHANNEL (IBOC) SYSTEM AND METHODS OF OPERATION USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM) WITH TIMING AND FREQUENCY OFFSET CORRECTION

5   Inventors: Robert Louis Cupo and Muhammad R. Karim

BACKGROUND OF THE INVENTION

1. Field of the Invention:

10   This invention relates to communication systems. More particularly, the invention relates to IBOC systems using OFDM with timing and frequency offset correction.

2. Description of Prior Art:

IBOC systems enable digital signals to fit within the bandwidth or frequency allocation

15   of existing AM and FM stations. IBOC systems preserve frequency spectrum by using existing allocations efficiently to deliver digital sound without disrupting AM and FM broadcasting. IBOC systems are subject to multipaths for the interference of signals, delayed upon themselves, due to reflections from man-made structures, such as buildings or from natural features, such as hills and trees. One method of minimizing the effect of multipaths is the use of Orthogonal

20   Frequency Division Multiplexing (OFDM) technique. OFDM is a form of multi-carrier modulation where carrier spacing is carefully selected so that each sub-carrier is orthogonal to the other sub-carriers. In OFDM, the total signal frequency band is divided into N non-overlapping frequency sub-channels. Each sub-channel is modulated with a separate symbol and, then, the N sub-channels are frequency-division multiplexed. There are three schemes used

25   to separate the modulated sub-carriers: (1) The use of filters to completely separate sub-bands; (2) the use of staggered quadrature amplitude modulation (QAM) to increase the efficiency of band usage; and (3) the use of discrete Fourier Transforms to modulate and demodulate parallel data. The orthogonality of the sub-channels can be maintained and individual sub-channels can be completely separated by Fast Fourier Transforms (FFT) at the receiver when there are no

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Intersymbol Interference (ISI) and Intercarrier Interference (ICI) introduced by transmission channel distortion. One way to prevent ISI is to create cyclically extended guard intervals where each OFDM symbol is preceded by a periodic extension of the signal itself. When the guard interval is longer than the channel impulse response, or the multipath delay, the ISI can be

5   eliminated. Using cyclic prefix at the transmitter, one can determine OFDM frame boundaries. If there is a difference in the clock frequencies at the transmitter and receiver, there are two problems. First, the difference causes an uncertainty in the frame synchronization. Second, even if no error occurred in frame synchronization, there would still be significant errors at a data demodulator. What is needed in the art is a system to recover timing and data in an IBOC

10   system subject to timing and frequency offsets.

Prior art related to OFDM includes the following:

USP 5,732,113 entitled "Timing and Frequency Synchronization of OFDM Signals" to T.M. Schmidl et al., issued March 24, 1998 (Schmidl), discloses timing, carrier frequency, and sampling rate synchronization of a receiver to an OFDM signal using two OFDM training

15   signals. A first OFDM training signal has only even numbered sub-carriers, and substantially no odd numbered sub-carriers, an arrangement that results in half-symbol symmetry. A second OFDM training symbol has even numbered sub-carriers differentially modulated relative to those of the first OFDM training signal by a predetermined sequence. Synchronization is achieved by computing metrics, which utilize the unique properties of these two OFDM training signals.

20   USP 4,604,583 entitled "Frequency Offset Correcting Circuit" to H. Aoyagi et al., issued August 5, 1986 (Aoyagi), discloses a frequency offset correction circuit in a demodulator which receives parallel channel signals and recovers each baseband signal of the parallel channel. The frequency offset correction circuit includes a second order phase-locked loop following a demodulating circuit arranged to detect baseband signals of incoming parallel channel signals.

25   The second order phase-locked loop include first and second control loops. The first control loop corrects a static phase shift of the pilot channel while the second control loop functions to correct abrupt frequency offset. The second order phase-locked loop is further utilized to correct both static phase shift and abrupt frequency offset data channels. A third control loop compensates for static or slowly changing frequency offsets of the channels.

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USP 5,444.697 entitled "Method and Apparatus For Frame Synchronization in Mobile OFDM Data Communications" to C. Leung et al. (Leung), discloses a method and apparatus for achieving symbol (frame) synchronization of digital data in an OFDM channel. A three-stage synchronization process is disclosed. First, an onset of an OFDM frame is detected. Second, coarse synchronization is achieved by sampling the received signal, and measuring the correlation between the received signal and a reference signal. Third, synchronization is achieved by calculating the time shift between the coarse synchronization point and the actual synchronization point and using the calculated time shift to determine the phase correction to apply to each data-carrying sub-carrier. The transmitted data is recovered by decoding the information obtained about the phase and amplitude of the data-carrying sub-carriers.

USP 5,771,224 entitled "An Orthogonal Frequency Division Multiplexing Transmission System and Transmitter and Receiver Therefor" to T. Seki et al. (Seki), issued June 23, 1998, discloses transmitting an OFDM frame with null symbols and reference signals placed at the beginning portion of the frame, and QPSK symbols placed in an information symbol data region in the frame with equal spacing in time and frequency. At a receiving end, an error detector detects amplitudes and phase errors of each carrier from the reference symbols and a variation detector detects the variations in the amplitude and phase of a received signal from the QPSK signals. The carrier amplitude and phase errors are corrected by a correction information producing section on the amplitude and phase variations of the received signals detected by the variation detector to produce correction information. An equalizing section equalizes the demodulated symbol data according to the correction information.

None of the prior art discloses correcting timing and frequency offset in OFDM systems working in the time domain after achieving frame synchronization by using an auto correlation function whereby nearly perfect cancellation of noise and multipath fading is achieved over a range of offset values.

SUMMARY OF THE INVENTION

An object of the invention is an improved IBOC system and method using OFDM having timing and data recovery in the presence of timing and frequency offset.

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Another object is an improved IBOC system and method of operation providing frame synchronization and timing and data recovery in the presence of timing and frequency offset.

Another object is an improved IBOC system and method of operation that provides a clock that is phase coherent with the transmitter for use at different points in a receiver.

5 These and other objects, features and advantages are achieved in an improved FM In-Band-On-Channel (IBOC) system using Orthogonal Frequency Division Multiplexing (OFDM) having timing and data recovery for correction of timing and frequency offset between transmitters and receivers. Offset causes OFDM frame synchronization and data demodulation errors. In the system, an OFDM receiver recovers an rf signal as in-phase (I) and quadrature phase (Q) components of a baseband signal. The components are sampled at a selected number

10 of points, e.g. 544 in an analog/digital converter. The output of the converter is stored in a two-deep FIFO. The I and Q components of a received symbol are correlated at all 544 sampling points. The correlation values are averaged over the latest L frames and saved in an L-deep FIFO. The amplitude and phase of the symbols are computed and passed to an offset estimator

15 and an OFDM frame synchronization estimator. The amplitude is used to estimate the frame boundary in the frame synchronization estimator which provides a frame pointer to a phase-locked loop oscillator designed to achieve fast OFDM frame synchronization. The phase-locked loop oscillator provides a sample number indicating the OFDM frame boundary to the offset estimator. An estimated offset value is selected as the negative of the phase angle of the auto

20 correlation function at the above sample number. The offset value is applied to the frame stored in the two-deep FIFO and identified by the sample number for correcting the time domain samples of the useful symbol period, after which the corrected samples are applied to the input of an FFT block and thence to a data demodulator. A programmable counter coupled to the phase locked loop locks the receiver clock to the transmitter clock.

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DESCRIPTION OF DRAWING

The invention will be further understood from the following detailed description of a

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preferred embodiment taken in conjunction with an appended drawing, in which:

Figure 1(a) depicts a frequency representation of OFDM sub-carrier signals using guard intervals.

Figure 1(b) depicts the time domain of Figure 1(a) with the added guar-period containing a cyclic prefix.

Figure 2(a) is a block diagram of a receiver in an IBOC system using OFDM and incorporating the principles of the present invention.

Figure 2(b) is a representation of a phase-locked loop in Figure 2(a).

Figure 3 is a flow diagram of an algorithm implemented in Figure 2(a0 for timing and data recovery for a hybrid FM IBOC system in the presence of timing and frequency offset.

Figure 4 is a table describing the performance of Figure 2(a) in terms of bit error rate under various conditions.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

In Figure 1(a) , multi-carriers 10 are modulated such that carrier spacing is carefully selected whereby each sub-carrier is orthogonal to other sub-carriers. In OFDM, the entire available bandwidth B is divided into a number of points $K = f_k \ldots f_n$, where adjacent points are or separated by a frequency band $f_s = \Delta f$, such that $B = K \Delta f$. In Figure 1(b), 543 K points are grouped into a frame 1 or frame 2 of K_1 points and two tail slots of K_2 points each, such that $K = K_1 + 2K$ and t_s is the useful symbol period. The frame carries the information intended for transmission under the form of Differential Phase-Shift Keying (DPSK) symbols or Quadrature Amplitude Modulated (QAM) symbols. Thus, each point in the frame corresponds to one information symbol. The two tail slots act as guard bands 11. The total symbol duration is $T = T_G + t_s$ where T_G is the guard interval and t_s is the useful symbol duration. The ratio of the guard interval to the useful symbol duration is application dependent. The insertion of guard interval will reduce data throughput, T_G, usually less than $T/4$. Although not shown in the

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Figure, the symbols are overlapped in the frequency domain but are separated by the guard interval in the time domain. A digital communication system using OFDM is described in USP 5,841, 813 issued November 24, 1998, assigned to the assignee of the present invention and fully incorporated herein by reference.

5   Turning to Figure 2(a), an IBOC system 12, as generally described in USP 5757854 and 5850415, includes a transmitter 14 coupled through an antenna 15 and an RF amplifier- down converter- filter 16 to a receiver 18 using OFDM as previously described in connection with Figures 1(a) and (b). The transmitter uses cyclic prefix or guard rings which determine OFDM frame boundaries for frame synchronization. Both the transmitter 14 and the receiver 18 include

10   a clock (not shown). When there is a difference in the clock frequencies at the transmitter and receiver, there are two problems. First the difference causes an uncertainty in frame synchronization. Second, there may be frequency offset between the local oscillator and the transmitter and the local oscillator and this receiver which causes sampling errors of the same amount in the frequency domain. The result is an increased Bit Error Rate (BER) with

15   significant data errors at the receiver. A feature of the invention is an IBOC system which corrects the problems of frame synchronization and frequency offset. An OFDM system, unlike well-known binary FM systems, does not explicitly provide bit timing information and, as such, does not lend itself to conventional clock derivation techniques. However, the present invention provides a way to derive a clock that is phase coherent with the transmitter which can be used at

20   different points in the receiver.

An rf modulated signal 17 is received at the receiver 18 and processed in accordance with OFDM. The signal 17 is recovered as an In Phase component (I) and a Quadrature Phase component (Q) of a baseband signal 20 by the unit 16. The I and Q outputs are each provided to standard analog-to-digital converters 24^1 and 24^2, respectively responsive to receiver sampling

25   clocks 26^1 and 26^2, respectively. The (I) and (Q) components of the received signal are each sampled in the converter s at 544 points using the receiver sampling clocks. The output of the converter 24 is provided to a standard 2-frame FIFO 28 which then feeds into an offset correcting circuit 30 and a correlator 32. Starting from the first sample in the FIFO 28, a complex

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auto-correlation function R_i of the I and Q components of the received symbol is computed for

$i = 0,1,...,543$ in the following way. Let z_k be the received $k - th$ sample

$$z_k = x_{I,k} + jx_{Q,k}$$

where $x_{I,k}$ and $x_{Q,k}$ are, respectively, the I and Q components of the received sample. Then

$$R_i = \sum_{k=i}^{i+31} z_k z_{k+512}^*$$

where z_k^* is the complex conjugate of z_k. Values of R_i for L latest frames are saved in the L-frame FIFO 34. Suppose $R_i(j)$ is the value of the auto-correlation function R_i of the $j - th$ frame of that FIFO. Its average value $\overline{R_i}$ is then computed as

$$\overline{R_i} = \sum_{j=1}^{L} R_i(j).$$

The amplitude and phase components of $\overline{R_i}, i = 0,1,...,543$ are provided to an OFDM frame synchronization estimator 36 and an offset estimator 38. The frame synchronization estimator 36 uses the amplitude of the auto-correlation function to estimate the frame boundary. The index at which the amplitude of $\overline{R_i}$ is maximum for all i with $i = 0,1,...,543$ gives the estimated frame boundary. For each incoming frame, this index which is actually a pointer to a specific sample of that frame is provided to a digital phase-locked loop 40 which generates a sample number indicating the desired OFDM frame boundary.

As shown in Figure 2(b), the phase-locked loop works in the following manner. Suppose that at any instant p_1 and p_2 are, respectively, the estimated frame boundary that is applied to the input of the phase-locked loop and the desired frame boundary at the output of the loop. Depending on the difference between the instantaneous values of p_1 and p_2, the loop gain is dynamically adjusted in each symbol period. The difference $p_1 - p_2$ is obtained in summing circuit 41 and saved in a FIFO 42. The saved differences are averaged over eight latest frames and passed through a first-order lead-lag filter 43, integrated in a modulo integrator 44, rounded off to the nearest integer value, and amplified in amplifier 45. The amplifier provides an input to a counter 46 which provides the sample number for the desired frame boundary p_2. The

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amplifier also provides to an external programmable counter 47 an output signal p_2, locked to the transmitter signal p_1 in the phase locked loop.. The counter 47 is responsive to a clock 48 and provides a receiver clock chain output phase locked to the clock of the transmitter.

5   The above frame boundary p_2 is provided to the offset estimator 38 and the offset correction circuit 30. In the offset estimator 38, the offset is estimated as the negative of the phase angle of the auto correlation function R_i for $i = p_2$. Let ϕ be this estimated offset. Values of ϕ and p_2 are provided to the offset correcting circuit 30 which modifies the amplitude and phase of each sample stored in the FIFO 28 to correct for frequency synchronization, frame

10   synchronization, and transmitter/receiver frequency offset in the following manner. Let

$$\theta_k = 2\pi\phi k / 544, \ 0 \le k \le 543.$$

Then the corrected symbol is given by

$$\hat{z}_k = x_{I,k} \cos \theta_k - x_{Q,k} \sin \theta_k + j[x_{I,k} \sin \theta_k + x_{Q,k} \cos \theta_k].$$

The output of the correction circuit 30 is provided to an FFT block and a data

15   demodulator 46 which provides data recovery for the IBOC system in the presence of timing and frequency offset between the transmitter and the receiver 18.

In Figure 3, an algorithm 50 is implemented in the receiver 18 to correct for timing and frequency offset in the OFDM baseband signal, as follows:

In step 1, the OFDM baseband signal is received and filtered. Analog/digital conversion

20   is performed and the in-phase (I) and quadrature phase (Q) components of the received baseband signal are sampled at a selected number of points and saved in a two-frame FIFO for processing by a correlator.

In step 2, in the correlator, starting from the first sample, the auto correlation values of the I and Q components are computed.

25   In step 3, the auto correlation values are stored in an L-word FIFO wherein the values are averaged over the L symbols to calculate the amplitude and phase for the frame.

In step 4, the amplitude of the auto correlation function is used to estimate the frame boundary which is applied to a phase locked loop oscillator. The output of the oscillator gives the

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sample number indicating the correct frame boundary.

In step 5, an offset estimator uses the negative of the phase angle of the auto correlation function at the sample number as the estimated offset.

In step 6, an offset correction circuit uses estimated offset in step 6 to adjust the phase angle of each sample n of the two-frame FIFO by an amount proportional to n, n being counted from the correct frame boundary provided by the phase locked loop oscillator.

In step 7, the guard interval or cyclic prefix is removed and the remaining samples of a symbol period are subjected to a Fast Fourier Transform (FFT) and demodulated.

In Figure 4, the Bit Error Rate (BER) for the receiver is shown in a table for various test conditions 1 - 11 of noise and fading. At test conditions 1 and 2, without noise or fading, but in the presence of the frequency offset which is left uncorrected at the receiver, the bit error rate is 0.1 and 0.35 for an offset of 0.3 and 0.5, respectively, where the offset is expressed as a fraction of the frequency of separation between adjacent sub-carriers. In this case, the BER is so high that the data is virtually unusable. At test condition 3, for a 10B Signal to Noise Ratio without offset or fading, the BER is very small as predicted theoretically. At test condition 4, both noise and a frequency offset of 0.5 have been added to the transmitted signal, but at the receiver, the offset has been corrected. In this case, the resulting BER reduces to the same level as for the case without any offset (i.e. test condition 3). In other words, the offset seems to have been corrected perfectly.

Test conditions 5-7 show that if there are various degrees of fading but no frequency offset, the BER performance worsens significantly compared to test condition 3, but not as much as with offset as indicated in test conditions 1 and 2. In this case, a BER of 3% is not unusual. With fast fading, e.g., a rural model with a mobile velocity of 150 km. per hour with a Doppler shift of about 13 Hz., the BER is worse than for slow fading, e.g., with an urban slow model with a mobile velocity of 10 km. per hour with a Doppler shift of about 0.87 Hz.

Comparing test conditions 8 and 1, fading further adds to the BER so that if the frequency offset is not corrected, the received data is not usable.

Comparison of test conditions 9 and 8 shows that with the offset correction, the BER improves by an order of magnitude. Similarly, comparing conditions 9 - 11 with conditions 5 - 7,

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it can be seen that when offset is corrected, the BER in the presence of fading becomes lower than that for the simple case of fading without added offset, again indicating that the offset has been cancelled perfectly. The improvement in performance with offset correction becomes more significant at higher mobile velocities.

5   While the invention has been shown and described in a preferred embodiment, various changes may be made therein without departing from the spirit and scope of the invention as defined in the appended claims in which:

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We claim:

CLAIMS

1   1.   An OFDM receiver, comprising:

2   means for recovering and sampling an rf signal into in- phase (I) and quadrature

3 phase (Q) components of a baseband signal;

4   means for computing auto correlation amplitude and phase values of the I and Q

5 components at sample points;

6   means for averaging the auto correlation values of the I and Q components over L

7 symbols;

8   means for providing a sample number indicating an OFDM frame boundary using

9 the averaged I and Q auto correlation values;

10   means providing an offset value indicative of the phase difference between the

11 receiver and a transmitter; and

12   means for correcting frequency and timing offset between the receiver and the

13 transmitter in the sample number .

1 2. The OFDM receiver of Claim 1 further comprising:

2   means for estimating frame synchronization of the OFDM frame boundary.

1 3. The OFDM receiver of Claim 1 further comprising:

2   means for phase locking the transmitter and the receiver.

1 4. The OFDM receiver of Claim 1 further comprising:

2   means for estimating the transmitter and receiver frame offset.

1 5. The OFDM receiver of Claim 1 further comprising :

2   means responsive to the sample number and a negative phase angle of the auto
3 correlation values for correcting for frequency synchronization, frame synchronization,
4 and transmitter/receiver frequency offset.

1   6. The ODFM receiver of Claim 1 further comprising:

2   means responsive to a sampling clock for generating the I and Q of the received

3   signal.

1   7. The OFDM receiver of Claim 1 further comprising:

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3   means for storing the sampled I and Q components coupled to the auto correlation

4   means and a correcting means.

1   8. The OFDM receiver of Claim 1 further comprising:

2

3   means for storing the averaged auto correlation values coupled to an offset

4   estimator and a frame synchronization estimator.

1   9. The OFDM receiver of Claim 1 further comprising:

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3   a phase locked loop comprising:

4   means responsive to a first and a second frame synchronization signal for

5   providing a difference signal indicative of the frame difference between the transmitter

6   and receiver ;

7   means for averaging differences over a series of frames as a frame difference

8   output;

9   means for processing the frame difference output through a filter ;

10   means responsive to the filter for integrating and rounding off the frame

11   difference output to the nearest integer value; and

12   counter means responsive to the integer value providing a sample number for a

13   desired frame boundary.

1   10. The OFDM receiver of Claim 9 further comprising;

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3   amplifier means responsive to the means for integrating and rounding off

4   providing a coherent clock signal for the transmtter and the receiver.

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11. The OFDM receiver of Claim 10 further comprising;

a programmable counter responsive to the coherent clock signal and a receiver clock for generating a receiver clock chain phase locked to the a clock in the transmitter.

12. A method of correcting timing and frequency offset in an OFDM receiver, comprising the steps of :

sampling in-phase (I) and quadrature phase (Q) components of a baeband signal;

computing auto-correlation amplitude and phase values of the I and Q components;

estimating a frame boundary of the received signal;

providing a sample number indicating a correct frame boundary;

estimating frequency and timing offset in the sample number of the receiver and a transmitter; and

correcting the frequency and timing offset in the sample number.

13. The method of Claim 12 further comprising the step of:
using the amplitude of the auto-correlation function to estimate the frame boundary.

14. The method of claim 12 further comprising the step of:

using the negative of the phase angle of the auto-correlation value as an estimated frequency offset at the sample number .

15. The method of Claim 12 further comprising the step of:

   applying the estimated frame boundary to a phase-locked loop.

16. The method of Claim 12 further comprising the step of:

   generating a coherent phase clock signal for the transmitter and the receiver.

17. The method of Claim 12 further comprising the steps of:

   storing the I and Q component values;

   providing the stored I and Q values for auto-correlation; and

   providing the stored values for offset correction.

18. The method of claim 12 further comprising the steps of:

   storing the auto correlation values;

   providing the auto-correlation values to a frame estimator;

   providing the auto-correlation values to an offset estimator.

19. The method of Claim 12 further comprising the steps of:

   adjusting the phase angle of each sample in a storing means by an amount proportional to "n" where "n" is counted from a correct frame boundary.
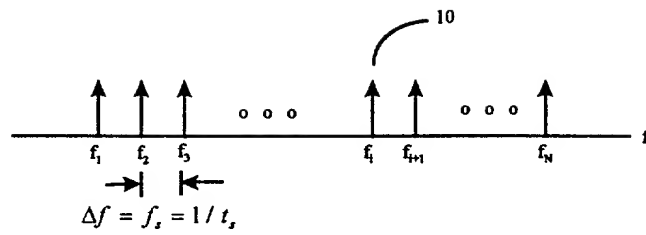
20. The method of Claim 12 comprising the step of:

   averaging the auto-correlation values over frames in a storage device.

21. In an IBOC system including a filter coupled to a converter, a first storage means coupled to the converter and to a correlator, a second storage means coupled to a frame synchronization estimator and an offset estimator, a phase locked loop coupled to the frame synchronization estimator and to the offset estimator, and an offset correction means coupled to the first storage means, the offset estimator and the phase locked loop, a method of correcting timing and frequency offset between a transmitter and a receiver in the system, comprising the steps of:
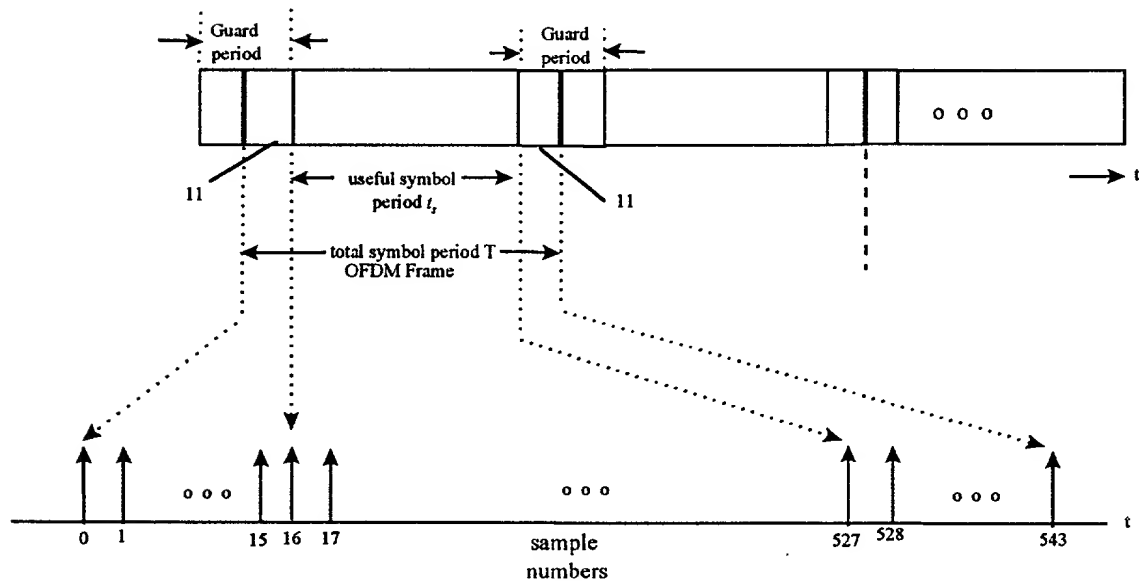
14

8   sampling in-phase (I) and quadrature phase (Q) components of a received

9   signal;

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11   computing auto-correlation amplitude and phase values of the I and Q

12   components;

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14   estimating a frame boundary of the received signal;

15

16   providing a sample number indicating a correct frame boundary;

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18   estimating the transmitter and receiver frequency and timing offset in the sample

19   number; and

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21   correcting the frequency and timing offset in the sample number.

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ABSTRACT

An improved FM In-Band-On-Channel (IBOC) system using Orthogonal Frequency Division Multiplexing (OFDM) has timing and data recovery for correction of timing and frequency offset between transmitters and receivers. Offset causes OFDM frame synchronization and data demodulation errors. In the system, an OFDM receiver recovers an rf signal as in-phase (I) and quadrature phase (Q) components of a baseband signal. sampled at a selected number of points, e.g. 544 in an analog/digital converter. The output of the converter is stored in a two-deep FIFO. The I and Q components of a received symbol are correlated at all 544 sampling points. The correlation values are averaged over the latest L frames and saved in an L-deep FIFO. The amplitude and phase of the symbols are computed and passed to an offset estimator and an OFDM frame synchronization estimator. The amplitude is used to estimate the frame boundary in the frame synchronization estimator which provides a frame pointer to a phase-locked loop oscillator designed to achieve fast OFDM frame synchronization. The phase-locked loop oscillator provides a sample number indicating the OFDM frame boundary to the offset estimator. An estimated offset value is selected as the negative of the phase angle of the auto correlation function at the above sample number. The offset value is applied to the frame stored in the two-deep FIFO and identified by the sample number for correcting the time domain samples of the useful symbol period, after which the corrected samples are applied to the input of an FFT block and thence to a data demodulator. A programmable counter coupled to the phase locked loop locks the receiver clock to the transmitter clock.
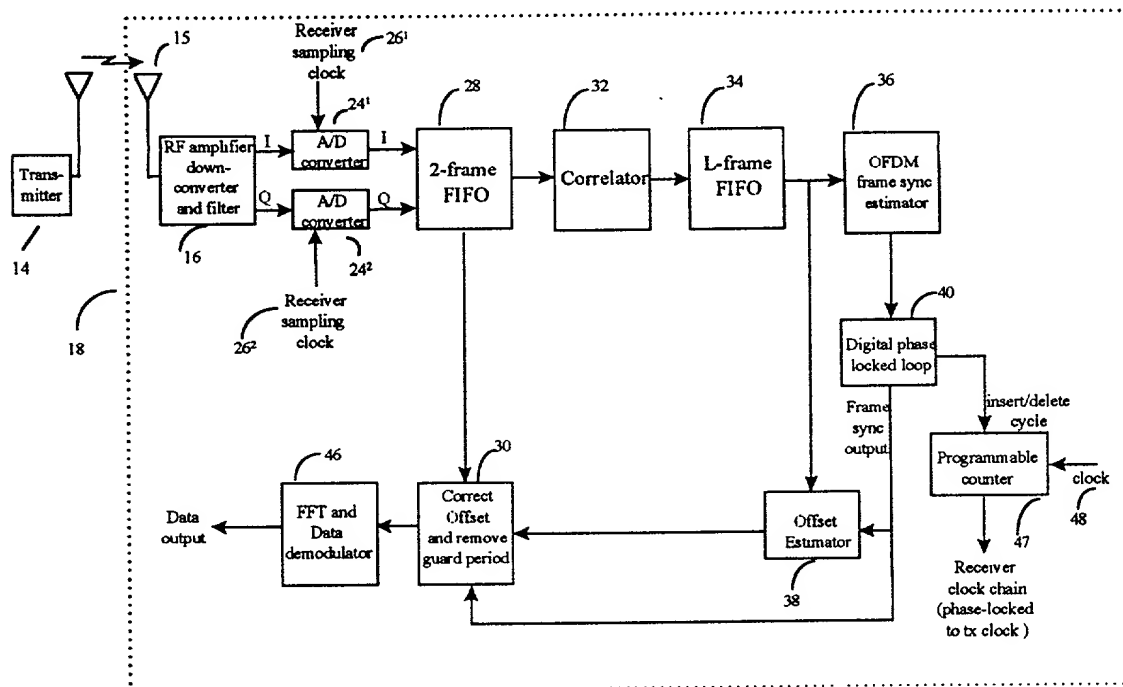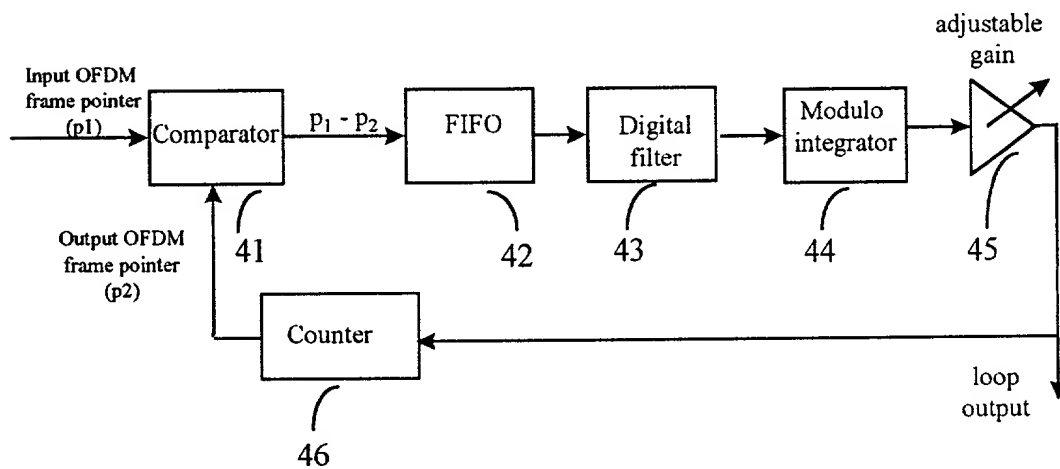
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Figure 1. The OFDM signals. (a) frequency domain representation of the OFDM sub-carriers. (b) The time domain signal with the added guard-period containing the cyclic prefix.

(a)

(b)

Figure 2. Offset correction procedure. (a) Functional block diagram of the algorithm. (b) Block diagram of the phase-locked loop.

Sample in-phase and quadtrature components of the received baseband signal at 544 points and save them in a 2-frameFIFO — step 1

Starting from the first sample of above FIFO, compute auto-correlation and save in an L-deep FIFO — step 2

Average auto-correlation values over the L frames — step 3

Using amplitude of the auto-dorrelation function, estimate frame boundary and apply it to a phase-locked loop. The loop output gives the sample number indicating correct frame boundary. — step 4

The negative of the phase angle of the auto-dorrelation function at above sample number is the estimated offset. — step 5

Use above estimate to adjust phase angle of each sample n of the 2-frame FIFO by an amount proportional to n, n being counted from the correct frame boundary — step 6

Remove cyclic prefix and take FFT of the remaining samples of a symbol period and demodulate. — step 7

Figure 3. Summary of the algorithm.

test conditions	Noise	Offset	Fading	Offset correction	Bit Error Rate
1	No	0.30	No	No	0.1
2	No	0.5	No	No	0.35
3	10 dB SNR	No	No	-	0.000020
4	,,	0.5	No	Yes	0.000020
5	,,	No	Urban slow	-	0.01673
6	,,	No	Urban Fast	-	0.01325
7	,,	No	Rural	-	0.04763
8	,,	0.30	Urban slow	No	0.15000
9	,,	0.30	Urban slow	Yes	0.01500
10	,,	0.30	Urban fast	Yes	0.01022
11	,,	0.30	Rural	Yes	0.03727

Figure 4. BER performance under different test conditions.

IN THE UNITED STATES
PATENT AND TRADEMARK OFFICE

Declaration and Power of Attorney

As the below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

We believe that we are the original, first and joint inventors of the subject matter which is claimed and for which a patent is sought on the invention entitled **"AN IMPROVED IN-BAND-ON-CHANNEL (IBOC) SYSTEM AND METHODS OF OPERATION USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM) WITH TIMING AND FREQUENCY OFFSET CORRECTION"** the specification of which is attached hereto.

We hereby state that we have reviewed and understand the contents of the above identified specification, including the claims, as amended by an amendment, if any, specifically referred to in this oath or declaration.

We acknowledge the duty to disclose all information known to us which is material to patentability as defined in Title 37, Code of Federal Regulations, 1.56.

We hereby claim foreign priority benefits under Title 35, United States Code, 119 of any foreign application(s) for patent or inventors' certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

None

We hereby claim the benefit under Title 35, United States Code, 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, 112, we acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

None

We hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

6003_1

We hereby appoint the following attorneys with full power of substitution and revocation, to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected therewith:

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We hereby appoint the attorneys on ATTACHMENT A as associate attorneys in the aforementioned application, with full power solely to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected with the prosecution of said application. No other powers are granted to such associate attorneys and such associate attorneys are specifically denied any power of substitution or revocation.

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